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U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS—BULLETIN NO. 79.
MILTON WHITNEY, Chief.

THE COLOR OF SOILS.

BY

W. O. ROBINSON, Scientist in Soil Laboratory Investigations,
and W. J. McCAUGHEY, Scientist in Soil
Laboratory Investigations.

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1911.

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1862 1889

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., January 18, 1911.

Sir: I have the honor to transmit herewith a manuscript entitled "The Color of Soils," by W. O. Robinson and W. J. McCaughey, scientists in soil laboratory investigations, of this bureau. This manuscript describes the results of investigations undertaken to determine the causes for the coloration of soils, with special reference to red and yellow soils, and their relation to properties of the soils determining differences in productiveness as observed in the work of the soil survey. The facts established are of a character to make advisable placing them at the disposal of other soil investigators, and I therefore recommend that the manuscript be published as Bulletin No. 79 of this bureau.

Very respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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THE COLOR OF SOILS.

INTRODUCTION.

The color of soils has long occupied the attention of both geologists and agriculturists and has considerable importance theoretically and practically. Theoretically the color is of importance as a guide to the origin and processes involved in the formation of the soil and as an indication of the relative age of any particular soil. It is of practical importance because it determines to a greater or less extent the absorption of the sun's energy, and is often a guide to the drainage conditions, to the crop adaptations, and to the cultural methods best suited to the soil.

It is the object of this bulletin to publish the results of an investigation into the causes of certain colors in soils, and particularly the causes of differences in color between the popularly named "red" and "yellow" soils in connection with the agricultural significance of such differences. In addition to this, certain of the chemical and physical properties of iron compounds and their solutions will be considered.

It must be recognized that soil colors are not pure colors, but at best are shades and tints. Thus the material by which soils ordinarily considered red are colored is ferric oxide, which itself is never a pure red, for it varies from dark brown to yellowish, and when in the soil it is further tinted and shaded by other materials. When applied to soils the color descriptions used in this bulletin mean the tints and shades which for the sake of simplicity are termed "red," "yellow," "brown," "black," or simple combinations of these.

In soils it is possible to find almost any conceivable color (from white beach sand to the black mucks of the swamp or the "rich" color of soils long kept under highly intensive cultivation. It is possible, however, to single out a few characteristic colors, like white, red, and black. Genetically considered, the color of most soils is dependent primarily upon the relative content of white minerals and content of organic matter, ordinarily black or red ferric oxide, or both. That is, that soils generally fall into one of three color groups. This classification can be expressed conveniently by a triangular diagram (fig. 1).

In this classification all soils are assumed to be made up of varying amounts of materials having the three fundamental soil colors, white, black, and red. These colors are represented by extreme kinds of soil, such as a pure white quartz sand, a black muck, or a red ocher. If the three fundamental coloring substances be assumed as 100 per cent at the apices of an equilateral triangle, then the color of practically all soils is determined (approximately at least) by some point in the triangle.[a] Whitish or gray soils are not generally of much agricultural value for general field crops, though sometimes of very great value for special purposes. In humid climates such a color indicates immediately that the soil lacks organic matter. In general it has a very high content of silica and alumina and very small content of iron or other colored oxides and organic matter. In arid regions the so-called alkali sometimes accumulates in white spots, frequently inhibiting the growth of plants. Occasionally a high content of gypsum gives some soils of arid regions a white or light-gray appearance.

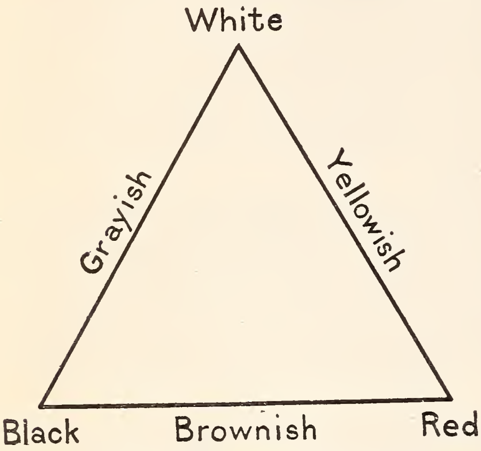

FIG. 1.—Diagram showing relation of soil colors.

Yellowish soils are very common, although a truly yellow soil is rather rare. It is generally considered that they owe their color to small amounts of ferric oxide, more or less hydrated. Black soils are universally esteemed highly. They are characterized by a high percentage of organic matter and frequently a comparatively high percentage of lime. The color is thought to be due to the formation of black humus bodies by the interaction between decaying organic compounds and the lime or other bases in the soil.

In the cotton States red soils are much in favor for agricultural purposes. Hilgard[b] states that the color implies good drainage, for otherwise the ferric oxide, which is the chief cause of the color, would be dissolved away by the stagnant waters.

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[a] This diagram must not be confused with a pure color diagram. Yellow, for instance, is a primary color and can never be realized in a mixture of red and white, but by actual experiment a soil made by an intimate mixture of a red soil and a white or light gray soil is yellowish in color.

[b] Soils, 285 (1906).

In the States south of Pennsylvania and east of the Mississippi there are many occurrences of soils of a bright red color. This color is also common in the Bahama Islands, and in southern Europe, where exist the Karst deposits known as "terra rossa." In the cotton States it is common to find, intermingled with these bright red colors, yellow, brown, blue, and green in the same bank.

It is generally held[a] that the coloring matter of sandstones and soils consists of a film of colored oxides, hydroxides, and organic matter surrounding the soil particles. The appearance of microscopic sections of red sandstones and the fact that red sands may be rendered entirely white by acid digestion[b] have led to these opinions. The difficultly soluble constituents of the soil solution are deposited upon and in the soil particles as the solution becomes more concentrated in dry periods; and from the compact nature of the deposit and from chemical change, such as the change from ferrous to ferric compounds, this coating does not dissolve in the soil water as rapidly as it is deposited. Thus it seems that the general effect of variation in the concentration of the soil solution is to thicken the coating of the deposited material. If, however, conditions are so altered as to change the chemical nature of the soil solution, as may occur by bringing into play reducing agencies, the deposited covering may be entirely dissolved away; a fact well illustrated by the pure white sand grains found under leaf mold and pieces of decaying organic matter. The soil solution is richer in carbon dioxide than the surface waters; when ground waters seep to the surface they lose carbon dioxide and are no longer able to hold certain carbonates and oxides in solution and deposit them upon the soil grains. Solutions of ferrous salts deposit ferric hydroxide in a similar manner, through oxidation, when the solution comes in contact with oxygen. This same film deposition takes place when two solutions intermingle, one containing substances which will precipitate components of the other. Thus Spring[c] has shown that, in contact with air, water containing humic materials in solution will precipitate the iron from the very dilute solutions found in nature. Water containing substances of a colloidal nature, like bog waters, "meadow tea," and the like, deposit material upon the surfaces of the particles of the soil through which they filter.

THE SIGNIFICANCE OF COLOR FROM THE VIEWPOINT OF AGRICULTURE.

The color of a soil may indicate the presence of a component in itself of actual benefit to the plant. Light-colored clayey soils generally contain goodly amounts of potash, and real black soils contain organic material in abundance. Color may also indicate the manner of formation of a soil, or the parent rock strata from which it was formed.

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[a] See Hawes, Geol. New Hampshire, 3, part 10, page 240, Plate XII, fig. 6 (1878); Crosby, Boston Soc. Nat. Hist., 23, 219-220 (1875); Russell, U. S. Geol. Survey, Bul. 52.

[b] Phillipps, Quart. Jour. Soc. London, 38, 110 (1882).

[c] Bul. de L'acad. Roy. de Belgique (3), 34, 578 (1897).

As a physical property, color can be of direct agricultural value only through the effect that different colors have in radiating and absorbing heat and possibly in regulating light intensity, for many chemical and bacterial reactions are influenced by that factor.

The high quality of the wines made from grapes grown on red soils on the hillsides of northern Europe may be due to the greater amount of heat the grapes have had during the growing season. Wollny[a] found that plots strewn with a surface coating of coal were slightly warmer than adjacent plots strewn with pieces of white marble, which gave a good reflecting surface.

Dark soils as a rule absorb and radiate heat more rapidly than do the light-colored soils. Melons have been ripened in a very inclement climate by covering the soil with charcoal to a depth of an inch. In England, Hannay[b] leached a quantity of soot with water to remove all soluble material and sowed it in alternate strips upon a potato field. Before the vines had grown enough to shade the ground, the temperatures of the soil on sunny days were as follows:

	At a depth of—	
	2 inches.	8 inches.
	° *F.*	° *F.*
Soot	62	60
No soot	60	58.5

The geologist Bakewell,[b] while passing through Switzerland, noticed a deep section in a very dark schist from which the inhabitants procured a black earth to sprinkle over the snow to accelerate its melting in the spring. The summers in this region are very short and such methods are necessary to lengthen the growing season, so that crops can be grown. It is a well-known fact that black cloth laid upon the snow causes it to melt much faster, owing to the greater absorption of the sun's heat rays, which are mostly reflected by the white surface of the snow. These examples serve to show that the dark-colored soils absorb the heat of the sun more readily than the lighter-colored soils. Red soils, their color being near the "heat" end of the spectrum, absorb heat readily. In the early period of the growing season, before the cultivated crops shade the ground, or in the case of crops that do not cover the ground, this variance of heat absorption by different colored soils is a factor of considerable economic importance.

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[a] Forsch. Agr. Phys., **12**, 385 (1889).

[b] See Storer's Agriculture, **1**, 40.

EARLIER INVESTIGATIONS.

Throughout the cotton States there are, roughly classified, two great color groups of soil, the red and the yellow. The red soils or soils just overlying a red subsoil are popularly recognized as more fertile, and yield larger crops of a superior quality. The difference between these soils and the yellow soils of the same region has frequently excited comment, and in the following pages quotations will be given from the publications of some of the more prominent investigators in this field.

Crosby[a] states that the red and yellow soils owe their difference in color to a difference in degree of hydration of the iron oxides they contain. He believes that the higher-soil temperatures prevailing in the South have served to dehydrate the yellow limonite into hematite, thus causing the red color. The red color is superficial and gives way to yellow beneath, where the higher temperatures do not prevail. In a later contribution Crosby,[b] while in the main supporting his earlier views, introduces considerations of other modifying factors. He considers the normal color of all southern surface soils to be red and that the development of the red color is due to a spontaneous dehydration of the ferric oxide taking place over a long period of time. In many places erosive agencies have kept ahead of this spontaneous dehydration, and the surface has been eroded away, exposing the soil of more recent formation.

Smith[c] observes that the soils of the red lands are derived from the decomposed hornblende, gneiss, and slates. They are residual clays, containing quartz veins and seams originally occurring in the rocks of that region. The surface soil is of a deep chocolate-brown color. At 10 to 15 feet below the color is bright red, and this stratum is underlain by a stiff yellowish clay. The color of the freshly decomposed rocks is yellow. It becomes darker and more intense as weathering processes advance. The gray soils have resulted from the decay of rocks containing very little iron-bearing minerals.

Merrill[d] states that soils are colored by carbonaceous matter and iron oxides. He believes that the difference between the red and yellow soils is due, primarily, to a difference in hydration of the iron oxides, but not to this alone. He reasons that the deeper-red color of the surface soil may be due to relative greater abundance of the iron oxide. The iron oxides, on account of their less soluble nature, accumulate in the upper portions of the soil as a result of the greater weathering action, which has taken place at that point. A small amount of the colored oxide disseminated through a large portion of detritus would impart but little color; the larger the proportion of iron oxide the deeper the color. Brilliancy of color indicates advanced decomposition and geological antiquity.

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[a] Proc. Bost. Soc. Nat. Hist., **23**, 219 (1875).

[b] American Geologist, **8**, 72 (1891).

[c] Geological Survey of Alabama, 1881–82, p. 184.

[d] Rocks, Rock Weathering, and Soils, 373 (1906).

Russell[a] discusses the origin of the red color in sandstones and residual deposits. He believes that the red color of sandstones was developed by the subaerial decay of the original rock material, forming a red soil, which was later compacted into a red sandstone, and that the color was not developed by heat during the compacting process or deposited by infiltering waters.

Watson[b] finds that the color of ochers depends upon the chemical composition. The hematites give a deep-red ocher and the limonites give a yellow ocher.

Spring[c] states that the coloring matter of soils is not iron oxide alone, but rather a combination of iron oxides, alumina, lime, magnesia, and silica. This material he finds to be more brilliant in color and better able to resist weathering action than simple ferric oxide. This mixture of oxides becomes brick red on heating and magnetic when very strongly heated. Spring considers that ferric hydroxide deposited in the estuaries of saline lakes becomes dehydrated to hematite through the action of the saline waters, which have a dehydrating effect comparable to the effect of a rise in temperature.

Maxwell[d] discusses the variation of the color of the soils of the Hawaiian Islands. In substance, he states that the terms "red" and "yellow" soils are misleading and that there are all possible gradations between these colors. According to him, there is no hard and fast relation between the productivity and color of these differently colored soils, although there exists a popular notion that red soils are the more productive.

Maxwell attributes the formation of the laterites, or red earths of the Hawaiian Islands to the disintegrating action of sulphuric acid in volcanic steam upon the lavas. These have been decomposed into white calcareous products, grayish products composed mostly of silica, and yellowish or reddish products in which the coloring matter is mainly iron oxides in various degrees of hydration. It is proved by analyses that both red and yellow laterites of recent formation contain large percentages of sulphuric acid—in some cases over 1.5 per cent—and that the sulphuric-acid content diminishes with the age of the laterite. From these facts it is concluded that sulphuric acid was the active agent in the formation of these earths. According to Maxwell, the difference between the red and yellow soils is not a difference in the amount of iron these soils contain, but rather a difference in hydration of the iron oxide. The red soils have been formed directly from normal unaltered lavas undergoing decay in a hot dry climate. They are high in anhydrous iron oxide. The yellow soils have resulted from a decay of the same rocks under the influence of a moist climate.

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[a] Bul. No. 52, U. S. Geol. Survey (1889).

[b] Bul. No. 13, Georgia Geol. Survey (1906).

[c] Rec. Trav. Chim., **11**, 202 (1898).

[d] Special Bulletin A, Division of Agriculture and Chemistry, Expt. Sta. of the Hawaiian Sugar Planters' Association.

The reports of the various State geological surveys upon the clay deposits and the pottery industry[a] contain frequent references to the color of clays and pottery to which they burn. The substance of these reports is that red clays except in very few cases, as in Commerce, Mo., and Woodbridge, N. J., where the clay is colored red by organic matter, and yellow clays owe their color to the iron compounds they contain. Blue and green clays may contain iron; but the iron here is reduced to a ferrous state by organic matter and, perhaps, by reducing bacteria.[b] The highly refractory clays do not contain any appreciable amount of iron. The color to which clays will burn depends upon the amount of iron oxide present and upon the chemical activity—i. e., reducing or oxidizing—of the kiln in which the ware is burned.

Van Bemmelen[c] finds that the iron oxide is present in some soils as concretions and in others as a thin coating around the soil grains. In the first form it is very easily soluble in hydrochloric acid and in the other it is more difficultly soluble. He finds that a much larger proportion of the total iron of the yellow soil is soluble in dilute hydrochloric acid by digestion at 55° for ten minutes than in the red soil treated in the same manner. When the ferric oxide in the soil is more than 5 per cent and the soil shows no red color it is present as a covering on the clay particles.

Richardson,[d] in an explanation of the formation of the red color in the Upper Red Beds of the Black Hills, finds that the coloring matter of these formations is due to anhydrous iron oxide.

Hilgard[e] treats the color of soils from an agricultural viewpoint very fully. It is his opinion that red and yellow colors in soils are indications of their drainage conditions. Ferric hydrate can not long exist in soils under poor drainage conditions, because of the reducing and solvent action of the soil water. On the other hand, in a well-drained soil there is little reducing action on the iron oxide, and it is not dissolved away, but persists as a red pigment. Thus, in a region where the soil has been formed from the decay of rocks rich in iron minerals, a poorly drained soil is yellow or whitish, while a well-drained soil is red. He believes that yellow soils, like the red, owe their color to iron oxides, but that they are present in the former in smaller amounts.

Summarizing these earlier discussions it may be said that black or blackish soils of different shades owe their color to varying amounts of humic or organic substances formed by the decay, under oxidizing conditions, of the plant and animal tissues left in the soil; the presence of a considerable proportion of lime carbonate in the soil facilitates such decomposition and is indicated by a pronounced black color. Red and yellow soils owe their color principally to a coating of ferric oxide, more or less hydrated, on the soil grains. Two theories are extant. According to the first, the ferric oxide is more highly hydrated in yellow soils than in the red soils. According to the second, the difference in color is due to the relative amount of ferric oxide the soil contains, and there is no essential difference in the hydration of the ferric oxide in red and yellow soils, respectively.

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[a] See, for instance, Wheeler, Mo. Geol. Survey, **11**, 66 (1896); also Ries, Professional Paper No. 11, U. S. Geol. Survey, 27.

[b] See Beyerinck, Arch. Neerland Sci. Exact. Nat. (2), **4**, (1900).

[c] Zeit. anorg. Chem., **42**, 265 (1904).

[d] Jour. Geol., **11**, 365 (1903).

[e] Soils, 283–285 (1906).

SOLUBILITY, TRANSPORT, AND DEPOSITION OF FERRIC OXIDE.

Since ferric oxide is obviously of fundamental importance in determining the color of soils, it is desirable to present, even though somewhat briefly, an outline of the processes by which it is formed, transported in the soil, and segregated on the soil particles.

Iron is an important constituent of the rocks and minerals forming the earth's crust. According to F. W. Clarke,[a] it amounts to about 4 per cent. In the degradation and decomposition of the rock material to form soils, ferric oxide tends to accumulate in the latter because of its relatively low solubility. It forms generally in a very finely pulverulent state and tends to accumulate on or in the finest soil particles of "clay."[b] The greater part of the ferric oxide is derived from the ferromagnesian silicates, such as the pyroxenes, hornblendes, chlorites, biotites, etc., minerals which have been shown to dissolve and hydrolize most readily in water.[c] The readiness with which these minerals are decomposed is probably due to two facts: First, that magnesium salts generally are prone to hydrolize, as shown by the readiness with which they form "basic salts," and, second, that the ferrous iron which is replacing the magnesia to a greater or less extent, is readily oxidized to the practically insoluble and inactive ferric oxide. Some of the ferric oxide is probably derived from that which as such more or less replaces alumina in the acid radicals of many minerals. Some of it may come from other types of minerals in particular cases. For instance, it is well known that under certain conditions involving moisture and oxygen, iron sulphides, as pyrites or marcasite, is transformed to the sulphate, which immediately hydrolizes. The sulphuric acid leaching through the soil more rapidly than the ferric hydroxide, the latter is left behind as a coating on the soil grains. Practically all iron salts, both ferrous and ferric, are greatly hydrolized in water solution; consequently the soil displays a very marked selective absorption when brought into contact with such solutions, abstracting the iron very completely and generally the acid to a very much less extent. In fact, fairly complete separations of iron from solutions of its salts may be readily effected by percolating the solutions through soil filters.[a]

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[a] Data of Geochemistry, Bul. 330, U. S. Geol. Survey, p. 32 (1908).

[b] See Meyer, Landw. Jahrb., **29**, 913 (1900).

[c] Bul. No. 30, Bureau of Soils, U. S. Dept. of Agr. (1906).

Water containing much carbon dioxide dissolves ferrous minerals in a marked degree. Richard Müller[b] investigated the solubility of the components of several minerals in water containing carbon dioxide. Table I shows the percentage of the total ferric oxide extracted by the solution.

TABLE I.—*Solubility of ferrous iron bearing minerals extracted by carbonated water, according to Müller.*

Minerals.	Per cent FeO.	Minerals.	Per cent FeO.
Adularia	Trace.	Magnetite	2.429
Oligoclase	Trace.	Olivene	8.733
Hornblende	4.829	Serpentine	1.527
Magnetite	.942		

Table I gives the percentage of the total percentage of ferrous iron removed. Thus if a mineral contained 10 per cent ferrous oxide and the figures read 4.20 per cent, it would mean that 4.20 per cent of the 10 per cent present was removed by the solution. The film water acting on the soil grains behaves in many respects as if it were under pressure higher than the ordinary atmospheric pressure, and it seems reasonable to believe that the concentration of carbon dioxide in the water is greater than it would be in free water in contact with ordinary air above the soil. It is desirable, therefore, to get an idea of the solubility of the common-soil minerals in a solution of carbon dioxide under a slightly increased pressure, recognizing that the figures have but a limited value in a quantitative way.

In Table II are given the amounts of iron removed from certain mineral and rock powders by a percolating stream of water saturated with carbon dioxide under a pressure of 20 pounds per square inch. The percolating tubes were about 15 inches long and one-fourth inch in diameter.

TABLE II.—*Amount of ferric oxide removed from certain mineral powders by percolating water saturated with carbon dioxide at a pressure of 20 pounds per square inch.*

Minerals.	Fe_2O_3 per liter.	Minerals.	Fe_2O_3 per liter.
	Gram.		*Gram.*
Allanite	0.0064	Granite	0.0680
Amphibole	.0104	Mennacanite	.0216
Bronzite	.0048	Ocher	.0384
Chromite	.0408	Pyroxene	.0080
Epidote	.0096		

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[a] For a detailed discussion of selective absorption, see Bul. No. 52, Bureau of Soils, U. S. Dept. of Agriculture (1908).

[b] Untersuchung über die Einwirkung des kohlensaurehaltigen wassers auf einige mineralien und Gestine. Tschermack's min. Mittheilungen, 25, 1877.

From these figures it may be seen that carbonated waters dissolve noticeable quantities of iron from the mineral when merely percolating through the mineral powder; but in addition to the carbon dioxide, dissolved organic matter has a marked effect in increasing the iron content of soil water.[a]

In order to obtain some definite notion of the solubility of iron-bearing minerals in water containing decaying vegetable matter, a series of mineral powders were shaken up for a month's duration with water containing decayed wood and muck. After settling for some time the clear solution was analyzed for iron. The results are given in Table III.

TABLE III.—*Effect of decaying organic matter on the solution of iron in iron-bearing minerals.*

Minerals.	Fe_3O_2 dissolved per liter.	Minerals.	Fe_2O_3 dissolved per liter.
	Gram.		*Gram.*
Amphibole	0.0264	Mennacanite	0.0160
Bronzite	.0096	Ocher	.0336
Epidote	.0240	Pyroxene	.0032
Garnet	.0160	Siderite	Trace.
Hornblende	.0192		

The results in Table III compared with those in Table II indicate that decaying organic matter has a somewhat higher solvent action on the iron of ferrous minerals than has carbon dioxide. It might be objected that the two sets of experiments are not strictly comparable, as the solvent was in contact with the mineral powders for different lengths of time. It has been pointed out, however, that the concentration of a solution in such a case will be dependent upon a number of factors.[b] Therefore, nothing more is deduced from these figures of the relative effects of carbon dioxide and humus than that both agencies are effective in causing a solution of iron in the soil water.

It is evident from the foregoing experiments and from a survey of the literature[c] that the iron of the rock-forming minerals is dissolved to quite a marked extent by the various solvents percolating through the rocks and soils. This solvent action can take place only when oxidizing conditions are absent. This point will be discussed more fully later.

The dissolved iron is transported toward the sea only to a limited extent. Owing to the readiness with which it is oxidized to the slightly soluble ferric oxide, it is usually reprecipitated within a short distance, frequently filling crevices from which its parent mineral has been removed. Thus limonite pseudomorphs after pyrites are of common occurrence.

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[a] For the geological action of humic materials, see Julien, Proc. Am. Assoc. for the Adv. of Sci., **28**, 311–411 (Saratoga meeting, 1879).

[b] See Cameron, Jour. Phys. Chem., **14**, 320 (1910).

[c] Among the numerous references see: Kindler, Pogg. Ann., **37**, 203 (1836); Dubarre, Compt. Rend., **10**, 1775 (1845); Bischof, Chemical and Physical Geology, etc.

The chalybeate springs which occur so commonly are examples of the transport and deposition of ferric oxide. In an artesian well flowing near Hyattsville, Md., the water was found to contain iron equivalent to 0.0944 gram per liter of Fe_2O_3.[a] This well has been closed since the analysis was made; but from an open well about 200 yards away the water was recently examined for ferrous and ferric iron. Ferrous iron was found in abundance, but no ferric iron could be detected. On subjecting the water to diminished pressure carbon dioxide was given off and a yellowish-brown precipitate settled out, which proved to be the familiar hydrated ferric oxide.

Ferric hydroxide is one of the least soluble substances. In pure water and in aqueous solutions of chlorides, sulphates, and nitrates of the alkali metals its solubility can not be detected by the most refined methods. The presence of carbon dioxide alone in natural waters is not sufficient to dissolve ferric hydroxide, although it does increase the solubility of ferrous hydroxide.[b] Water charged with carbon dioxide is capable of carrying considerable amounts, as is illustrated by the high iron content of the water of the chalybeate spring referred to above. The iron in solution is probably present as ferrous carbonates.

Before ferric oxide can dissolve in water it must be reduced, a change effected by organic matter. Such a process can be observed in a red soil in the immediate vicinity of a root. There is a zone of a different color, and in extreme cases the root is surrounded by a residue of pure white soil grains. Such cases may be observed under the black leaf mold of the forest. According to Julien[c] the white beach sands on the coast of the Atlantic States owe their absence of color to a similar solvent action of the bog waters just back of the coast. Hilgard states that the accumulation of water containing organic matter, a consequence of poor drainage, soon changes the red color of a soil to yellow by its solvent action on the iron film.

It is clear, therefore, that ferric oxide can be reduced with comparative ease by soluble organic matter. In the absence of oxidizing conditions and in the presence of an excess of carbon dioxide in solution, the ferrous iron can be transported quite freely. Whenever a condition is realized favorable for the escape of carbon dioxide, by the agency of heat or reduced pressure, the solution is no longer capable of holding the iron, and ordinarily limonite or bog iron is deposited. Should this deposition take place during seepage through a soil, a colored layer is deposited upon the surfaces of the soil particles. In cases where there is a marked change of texture from the sandy surface soil to a heavier subsoil it is common to find so heavy a deposition of ferric oxide that it serves as a binding or cementing substance, forming a hardpan with the soil material.

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[a] Bul. No. 17, Bureau of Soils, U. S. Dept. of Agriculture (1901).

[b] Cameron and Robinson, Jour. Phys. Chem., 12, 56 (1908).

[c] Proc. Am. Assoc. for the Adv. of Sci., 28, 311-411 (1878).

Merrill[a] finds that the residual soil contains larger percentages of iron and aluminum than the parent rocks from which it was weathered, whereas ferric oxide is easily reduced, and in this condition, relatively soluble, it is concentrated in the most weathered geological formations, because under meteorological conditions the chemical reactions are oxidizing rather than reducing.

It thus appears that iron is not only dissolved from ferrous minerals, but that ferric compounds are continually being reduced and dissolved. Nevertheless, ferric oxide is one of the least soluble soil components and the general effect of weathering is to increase the iron content of the surface soil.

HYDRATION OF FERRIC OXIDE.

Hydrates of ferric oxide in nature are common and widely distributed. Mineralogists have long recognized a conventional series, as follows:

Hematite	Fe_2O_3	Limonite	$2Fe_2O_3.3H_2O$
Turgite	$2Fe_2O_3.H_2O$	Xanthosiderite	$Fe_2O_3.2H_2O$
Goethite	$Fe_2O_3.H_2O$	Limnite	$Fe_2O_3.3H_2O$

Of these, the first frequently occurs in well-characterized crystals, although often as an amorphous red mass or powder. Occurrences of goethite in crystalline form have been reported, but are unusual. Mixtures with all possible compositions lying between those indicated in the series are frequently found, and it seems to be generally conceded that no definite hydrate of ferric oxide exists. This opinion is supported by vapor-pressure measurements of van Bemmelen,[b] who found that at 15° C. the vapor-pressure composition isotherm for the system ferric oxide water is continuous, there being no breaks or sudden inflections to indicate the existence of a definite compound. To verify this conclusion, the vapor-pressure composition isotherm at 25° C. has been determined. The temperature was controlled within 0.1° and ferric oxide gels were allowed to stand for three months at definite vapor pressures, maintained by solutions of sulphuric acid of known composition. The data obtained are given in Table IV, and plotted in figure 2. There is no evidence of the formation of any definite compound.

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[a] Rocks, Rock Weathering, and Soils, 185–227 (1906).

[b] Rec. Trav. Chim., 18, 86 (1899).

TABLE IV.—*Composition of ferric hydroxide of varying vapor pressures at 25° C.*

Vapor pressure.	Fe_2O_3.	Vapor pressure.	Fe_2O_3.
Mm.	*Per cent.*	*Mm.*	*Per cent.*
23.54	7.84	10.00	74.05
22.00	10.85	8.00	77.60
20.00	60.01	6.00	79.30
18.00	67.68	4.00	82.01
16.00	69.87	2.00	83.19
14.00	70.82	.09	85.98
12.00	72.30		

Microscopic examination failed to show evidences of crystalline structure in any case. The only physical difference that could be observed was that the color was darker the less the proportion of water present. This gradation in color corresponds to that observed in the natural hydrates. Hematite itself is black when crystalline, though red by transmitted light, and its powder is red. Turgite is a deep brown; limonite is a light brown or yellow, and the intermediate hydrates have shades of color between these limits.

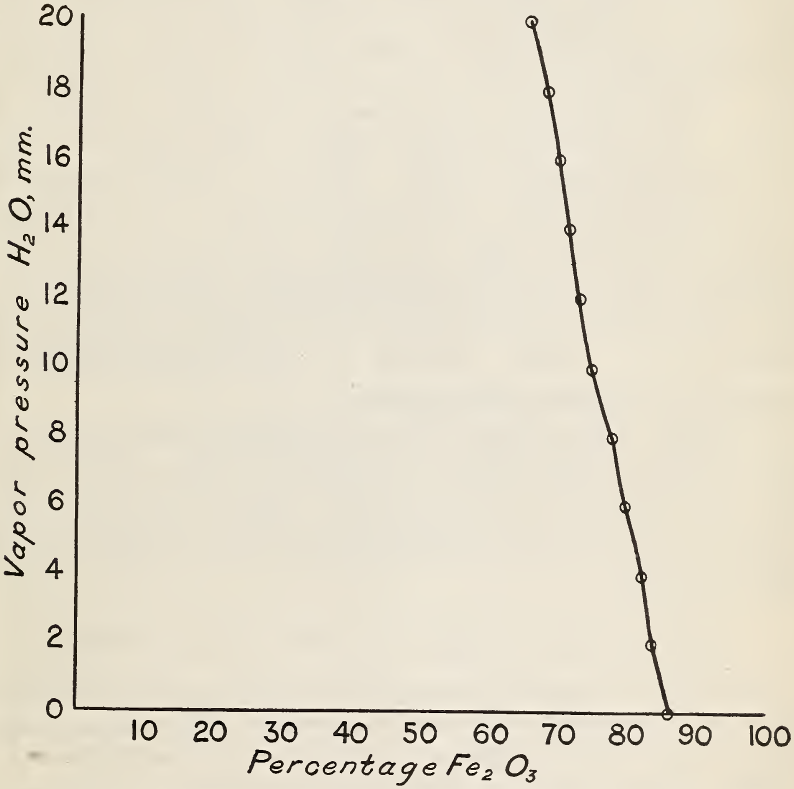

FIG. 2.—Showing the relation between vapor pressure and composition of hydrated iron oxides.

By heating limonite or any hydrate of ferric oxide, it loses water, changes color, and becomes, in fact, red hematite. There is, however, no satisfactory measurement of a temperature of inversion of limonite to hematite, and it is doubtful if such an inversion point exists. At ordinary pressures limonite does not lose water appreciably at any temperature which may be realized under field conditions.

The literature on ferric hydrates is voluminous and contradictory. It appears, however, from laboratory investigations that ferric hydroxide, when first precipitated, is dark red. On standing it apparently becomes more compacted, and the color changes toward the characteristic yellow of limonite. Tomassi,[a] who has done much work on this subject, divides ferric hydrates into two series, *a* and *b*. The red or *a* series is obtained by precipitation with alkalies from ferric solutions. This series is easily soluble in dilute acids and is dehydrated by boiling. The yellow or *b* series is realized by the oxidation of ferrous hydroxide, ferrosoferric hydroxide, or ferrous carbonate. The *b* series is sparingly soluble in dilute acids and retains the water of hydration on boiling. The red or *a* series represents the condition of the freshly precipitated hydroxide. On standing it becomes yellow and occupies less bulk. Freezing and thawing and boiling hasten the process. It is reasonable to assume that ferric hydroxide would assume this form in the soil. The hydration and dehydration of ferric oxide under soil conditions is further complicated by the possible activities of certain bacteria which are reported to dehydrate ferric hydrate.[b]

It appears, then, that the color of a hydrated ferric oxide is, in part at least, determined by its content of water. On the other hand, all the hydrates of iron develop a lighter color the more finely they are pulverized, and it would seem, therefore, that the color is largely determined by the thickness of the film through which the light penetrates.

CORRELATION OF COLOR AND FERRIC OXIDE CONTENT.

In Table V are given the total iron content and color of several soils. It is unfortunate that the data on this point are so meager. Few of the published complete soil analyses contain any reference to color.

From Table V it can be seen that there is a wide variation in the ferric-oxide content in soils of any one color, and while in general the red soils are higher in iron than are the yellow soils, there are exceptions. The Hawaiian soils, since they are very high in basic constituents, are not strictly comparable to the American soils.

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[a] Bul. Soc. Chim. (2), 38, 152.

[b] For an exhaustive discussion of this subject, see Gasperini, Atti. R. Accad. Geog. Firenze (3), 5, 503 (1906).

Table V.—*Color and ferric oxide content of certain soils.*

Color.	Ferric oxide.	Location.
	Per cent.	
Deep brown red	[a] 17.61	Harford County, Md.
Brownish red	[a] 19.20	Albemarle County, Va.
Do	[a] 13.33	Do.
Dark red	[b] 28.73	Hawaiian Islands.
Do	[b] 28.79	Do.
Red	[c] 13.90	Bermuda Islands.
Do	[c] 8.30	Morrisonville, Ala.
Red clay	[c] 15.16	Lexington, Va.
Distinctly red	[d] 12.70	Mount Hope, Md.
Do	[d] 6.04	Clifton, Ball County, Md.
Do	[d] 6.00	Mechanicstown, Md.
Do	[e] 11.81	Charlottesville, Va.
Light red	[d] 5.70	Mechanicstown, Md.
Yellow	[b] 26.93	Hawaiian Islands.
Do	[b] 43.11	Do.
Ocher yellow	[d] 10.56	Emmorton, Md.
Yellow	[d] 8.20	Cramptons Gap, Md.
Ocher yellow	[d] 6.61	Washington County, Md.
Distinctly yellow	[d] 6.58	Leitersburg, Md.
Yellow	[d] 2.44	Chaneyville, Md.
Distinctly yellow	[d] 2.54	Popes Creek, Md.
Yellow	[d] 4.90	Chewsville, Md.
Do	[d] 3.62	Hagerstown, Md.
Do	[d] 7.38	Do.
Do	[d] 4.98	Glenville, Md.
Distinctly yellow	[d] 3.20	Wye Mills, Md.
Yellow	[d] 3.55	Smithsburg, Md.
Do	[d] 4.40	Rock Run, Md.
Do	[d] 2.60	Centerville, Md.

[a] G. P. Merrill, Rocks, Rock Weathering, and Soils, 1909, pp. 207, 211, 214.

[b] Bul. Agr. Expt. Sta., Hawaiian Sugar Planters' Assn., Lavas and Soils of the Hawaiian Islands, pp. 57, 58–64.

[c] Cited from I. C. Russell, Subaerial Decay of Rocks, Bul. 52, Geol. Survey, pp. 24, 29, 40.

[d] Bul. 70, Maryland Agr. Expt. Sta.

[e] Analysis made by Bureau of Soils.

It seems from this table that the difference in iron oxide content does not account for the difference in color between the red and yellow soils, and in the cases cited two yellow soils run higher in iron oxide than do the red soils. These analyses are complete and show the iron present as iron-bearing minerals as well as the iron oxide content of the surface stain that gives the soil its color. It is possible that iron-bearing minerals have contributed largely to the iron content of the above soils not red or of deeper colors, and that we are not dealing only with the material which contributes to the color of the soil. In general, iron-bearing silicates are not much decomposed by acids. The surface iron stain of the soil particles is, however, entirely soluble in acids. The amount of iron removed from a soil by acid digestion would therefore be indicative of the thickness of the iron stain,[a] other things being equal, and fortunately such data are correlated with the color of the soils in a series of acid-digestion analyses given by E. A. Smith, in the Geological Survey of Alabama, 1881–82, pages 184–346, and also in the Geology of Arkansas, Second Report, page 175. Table VI contains a collection of such data, the color and iron content only being given.

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[a] This statement excepts, of course, soils which contain concretions of limonite or bog iron ore.

Table VI.—*Acid digestion of soils of Alabama and Arkansas.*

Color.	Fe_2O_3.	Color.	Fe_2O_3.
	Per cent.		*Per cent.*
Dark red	10.7	Yellowish gray	1.4
Red	9.3	Do	.8
Do	23.6	Yellow	2.7
Dark red	7.2	Light yellow	4.2
Red	5.0	Yellow	3.0
Do	6.1	Do	2.3
Do	5.0	Do	1.9
Deep red	4.9	Do	1.5
Brownish red	4.2	Gray	2.0
Reddish brown	5.5	Do	6.5
Do	3.7	Light gray	1.4
Deep red	2.5	Brownish gray	2.2
Red	2.6	Grayish brown	3.0
Dark red	2.4	Reddish brown	2.0
Reddish	1.9	Light brown	5.9
Light yellow	6.8	Do	2.9
Yellow	2.8	Dark brown	.7
Do	2.9	Do	5.6
Yellowish	.7	Dark brown to black	5.3
Yellowish gray	1.7	Yellowish brown	10.3
Do	2.7		

Averaging the samples of the red and yellow types, we obtain 7.2 per cent Fe_2O_3 for the red and 2.4 per cent for the yellow. It is unfortunate that the mechanical analyses[a] of these soils are not available, so that the depth of film of ferruginous material on the soil grains from the several samples might be compared with the color. It is evident that a film of coloring matter of a certain depth over large soil particles would contribute much less to the total percentage of the coloring matter than if a film of the same thickness was spread over the same weight of exceedingly fine particles; and since the film is postulated to be of the same thickness in each case, the color must be much alike in the two instances. The following laboratory experiment will serve to illustrate this point. Samples of 20 grams each of coarse white quartz sand, averaging 2 mm. in diameter, and white quartz flour were treated with ferrous-sulphate solutions of such a concentration that the dried material should contain from 0.1 per cent Fe_2O_3 to 2.5 per cent Fe_2O_3, with five intermediate percentages. The material was evaporated to a paste and enough ammonia added to precipitate the iron present. Hydrogen peroxide was then added to oxidize the iron and the material was heated to dull redness to drive off the ammonium sulphate and dehydrate the iron oxide. In this manner the iron oxide was deposited upon the surface of the quartz grains. The quartz flour containing 2.5 per cent Fe_2O_3 was very nearly matched in color by the coarse quartz sand containing 0.25 per cent Fe_2O_3.

For the purpose of comparing the percentage of iron removed by acid digestion with the mechanical analysis and the color of soils, a series of 21 representative American soils of distinctly red and yellow types were subjected to a mechanical analysis and a chemical examination for constituents, apart from organic matter, likely to color the soil. Table VII contains the data obtained from the analysis outlined above. The titanium and manganese analyses were made by Mr. W. H. Waggaman, of this bureau.

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[a] By mechanical analysis is meant the separation of the soil particles into conventional sizes and determining the percentage of weight of particles of certain sizes.

TABLE VII.—*Mechanical analysis and content of colored oxides of representative red and yellow American soils.*

Soil	Color.	Chemical.			Mechanical.							
		Fe_2O_3.	TiO_2.	MnO.	Gravel.	Fine gravel.	Coarse sand.	Medium sand.	Fine sand.	Very fine sand.	Silt.	Clay.
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
8833	Red	41.44	0.59	0.08	....	5	8	5	14	12	13	43
16478	.....do	8.96	1.10	.20	....	1	4	2	6	3	37	48
8118	.....do	3.20	.55	.03	....	1	4	7	34	15	5	34
14793	.....do	4.52	.95	.06	....	....	....	......	1	8	66	24
7180	.....do	15.32	1.10	.07	....	1	2	3	6	3	41	44
9230	.....do	6.60	.95	.08	....	2	7	6	12	9	19	44
5901	.....do	5.70	.95	.06	....	4	5	2	8	8	45	27
11942	.....do	6.56	.73	.07	....	....	1	3	8	5	37	45
11318	.....do	1.20	.46	.03	....	2	39	19	21	6	2	11
14417	.....do	1.44	.55	.04	....	1	18	13	29	11	14	13
5328	.....do	9.00	1.05	Trace.	4	4	4	2	5	3	19	53
10675	Yellow	.88	.33	.02	....	....	....	1	83	10	2	4
5875	.....do	4.72	.85	.14	1	1	2	2	4	2	47	36
13714	.....do	4.56	.98	.13	....	....	1	1	4	5	66	23
7841	.....do	3.20	.67	Trace.	....	3	20	11	24	4	5	32
5744	.....do	7.52	.73	.03	2	3	4	3	33	17	12	24
12827	.....do	3.32	.99	.18	....	2	5	2	5	6	38	42
6417	.....do	3.20	.68	.18	....	....	1	......	......	3	76	13
13338	.....do	3.24	.98	.11	....	1	2	1	11	14	38	32
6258	.....do	2.28	1.10	Trace.	....	....	....	......	10	17	42	30
13578	.....do	1.52	.22	.03	....	....	....	......	44	10	24	21

By inspection of Table VII it may be seen that Nos. 8118, 11318, 14417, and 14793 were the only red soils that did not contain over 5 per cent Fe_2O_3. These soils, excepting No. 14793, consisted mainly of large particles. Thus No. 11318 contained 87 per cent of particles larger than silt and clay. Nos. 5875 and 13714 were the only yellow soils that contained a very large percentage of iron, compared with the red, except No. 5744, and these soils contained 83 and 89 per cent of silt and clay, respectively. No. 5744 contained concretions of limonite, which accounts for the large content of iron.

Averaging the iron content of the red and yellow soils, we obtain 9.9 per cent and 3.4 per cent of Fe_2O_3, respectively. Of course the iron content of No. 8833 is abnormal, but it is used in computing the average because the series was selected with reference to color only before the analyses were made.

From the foregoing it appears that in general the difference in color between the red and yellow soils is due to a difference in the thickness of the film of the coloring material. No. 7841 is the only exception to this statement. There is slightly more titanium in the red than in the yellow soils; the manganese is about the same in both. It is doubtful if these elements have any influence on the color of the soil when present in such small and uniform amounts.

SEPARATION OF THE COLORING MATTER FROM THE SOIL.

It was pointed out earlier in the work that the suspensions in water (so-called clays) were more highly colored than the soil itself. During the process of mechanical analysis of soils carried out in this bureau, a number of the clay separates from red and yellow soils were collected and analyzed. The results are given in Table VIII.

By inspection of the table it can be seen that no distinctive uniform difference in composition exists between the samples chosen. The red clays average higher in ferric iron, but lower in ferrous iron, loss on ignition, and the more soluble constituents. There are so many water-holding constituents present that it is, of course, impossible to determine the state of hydration of the ferric oxide.

TABLE VIII.—*Comparison of chemical composition of red and yellow clays.*

Soil.	Fe_2O_3.	FeO.	Al_2O_3.	SiO_2.	CaO.	MgO.	Ignition loss.	$K_2O.Na_2O$[a].
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Yellow composite clay	5.95	1.87	28.14	55.39	1.93	1.36	14.44	5.36
Red composite clay	12.98	1.05	30.08	48.63	.88	.91	13.33	5.47
No. 10910, yellow	7.65	2.23	37.37	49.03	.50	.68	18.49	2.54
No. 9556, yellow	11.87	1.08	33.14	49.35	.40	.41	18.24	3.75
No. 9568, brownish red	9.07	.88	39.63	48.69	.45	.44	14.25	.84
No. 9570, red	18.48	.80	40.01	39.25	.20	.39	13.62	1.87

[a] By difference.

Owing to the differences in the specific gravity, and in the flocculating or deflocculating power of liquids, it was thought that by using different liquids a better separation of the soil constituents might be made. Portions of a typical red soil were shaken up with water, alcohol, chloroform, carbon tetrachloride, and ether. The mixture was allowed to settle one-half hour and the suspension decanted off. The process was repeated until the decantations became clear. The alcohol suspension was darker than any of the others, though the difference was slight. The iron, soluble in hydrochloric acid, in these suspensions was as follows: Water, 9 per cent; alcohol, 9.8 per cent; chloroform, 9 per cent; carbon tetrachloride, 9.4 per cent; ether, 8.2 per cent Fe_2O_3. Small amounts of hematite were separated from the dark-red sandy soil by means of Thoulet's solution, then washed generously with absolute alcohol and ether, and finally dried for a few minutes at 90° C. On analysis this material proved to be anhydrous ferric oxide, and gave a red streak.

Air elutriation was tried on a sample of red soil. The particles carried over to the last chamber, however, were no redder than the body of the soil and the iron content had decreased rather than increased. Air elutriation of a yellow soil gave no apparent concentration of the coloring matter.

Richardson[a] found that the coloring matter of the Red Beds of the Black Hills was iron oxide, and that this iron oxide was probably completely anhydrous. He states:

> Sample No. 54 [a red sandy shale] in which the complete analysis shows 2.84 per cent of combined water, was treated with hot hydrochloric acid until all the iron was dissolved. The residue was found to contain 1.90 per cent of combined water, leaving 0.94 per cent available for the hydrous minerals which hydrochloric acid would attack. Gypsum, and possibly an iron hydrate, were the only ones that acid would decompose. Calculating the amount of gypsum from the amount of SO_3 it was found that 4.8 per cent of the rock is gypsum. This requires 1 per cent of water, which practically is the amount available. No water, therefore, is left for combination with the iron. It is true that this combination is but an approximation, but it appears evident that the red pigment is anhydrous, or nearly so.

EFFECTS OF HEATING AND OF OXIDIZING AND REDUCING AGENCIES ON RED AND YELLOW SOILS.

On being heated in the air practically all soils become red. Soils already red usually deepen in color. This appears to show that the film of ferruginous material coating the soil grains is dehydrated and is converted more or less completely into ferric oxide.

If, however, the soils be heated in a stream of hydrogen they uniformly turn gray, and generally metallic iron can be detected. If the soil be heated in an inert gas or where there is an insufficient supply of oxygen, there is formed a banded structure. Where the heat has been most intense there is a gray band containing metallic iron. Beyond this is a zone of carbonization, then a yellow zone of partial reduction, and finally unaltered soil. Soils heated in an atmosphere of carbon monoxide behave much as in hydrogen, if heated for a sufficient length of time at a high temperature. But they show the banded structure at intermediate stages of heating. These facts are additional evidence that in practically all soils, excepting white sands, there is a coating of ferruginous material, and moreover, show that it is more or less mixed with organic substances. Under oxidizing conditions these soils will tend to become red or yellow, while under contrary conditions the same soils would tend to a gray color.

That the color is not due alone to the state of hydration of the ferruginous oxides is indicated by the fact that a red soil can under special conditions become yellow, although this transformation is not a usual one. The way in which it is brought about in nature is illustrated by the following experiment: A glass tube about 40 inches long and 1 inch in diameter, was half filled with a bright-red soil, and then filled to the top with leaf mold and decayed wood. Upon leaching the contents of the tube with distilled water, the soil column gradually became lighter in color and a considerable quantity of iron was found in the leachings. At the end of the experiment the upper end of the soil column had changed to a dull yellow. The most probable explanation is that a part of the film coating, the soil particles in the upper part of the tube, was reduced, dissolved, and leached away and the yellow color is the direct result of a thinner film only.

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[a] The Upper Red Beds of the Black Hills. Jour. Geol., **11**, 365

COMPARATIVE SOIL TEMPERATURES OF NORTHERN AND SOUTHERN STATES WITH RESPECT TO THE CHANGE OF LIMONITE INTO HEMATITE IN THE SOIL.

If, as Crosby suggests, the higher temperatures of the soil in the Southern States has served to dehydrate the iron oxide, whereas in the Northern States it remains hydrated, we would expect a wide difference in the soil temperatures of these States. Various forms of iron oxide retain their water at temperatures far exceeding 100° C., and it is hardly probable that any soil temperature would be high enough to change limonite into hematite if salt solutious or bacteria were not present to complicate the reaction. In Table IX are given soil-temperature data from several States.

Table IX.—*Soil temperatures of a few Northern and Southern States.*

Place.	Time.	Temperature.	Reference.
		°*F.*	
Uniontown, Ala	Aug., 1889	79	Alabama Canebrake Station Reports, 1889.
Raleigh, N. C	July, 1886	82	North Carolina Station Reports, 1886.
Geneva, N. Y	June, 1889	70	New York Station Reports, 1889.
Orono, Me	do	66	Maine Station Reports, 1889.

These soil-temperature data are very meager, and the temperatures were not taken at the same seasons of the year. They are the mean temperatures for the months during which they were taken. The difference between the soil temperature for the month of June at Orono, Me., and Raleigh, N. C., for the month of July, is but 16° F., and we may reasonably suppose this difference would be less had the temperatures been taken for the same periods.

It is apparent that there exists no sufficient difference in soil temperatures of the Northern and Southern States to cause a change from a hydrated to a dehydrated iron oxide; and if the change of a yellow soil into a red soil is due to dehydration, we certainly must look for other causes than a variation in soil temperature.

MINERALOGICAL EXAMINATION OF RED AND YELLOW SOILS.

A mineralogical examination was made of 20 distinctly red and yellow American soils. These soils were separated into grains of different sizes as in mechanical analysis, and determinations made on the fine sands (0.25 to 0.1 mm. diameter). All of the minerals present in any appreciable quantity were determined and the relative amounts approximated in some cases. Special interest was attached to the apparent state of weathering, decomposition, and alteration of the minerals, and particularly of the iron-bearing minerals. It is to be regretted that there is no satisfactory way of distinguishing limonite and hematite when in a very fine state of division and mixed with foreign material, so that the precise nature of the ferruginous coatings on the soil particles could not be determined.

The secondary quartz grains are characterized by included iron stains and do not possess the clear gaseous or liquid inclusions which characterize the primary quartz particles.

The minerals were determined microscopically, using the oil-immersion method. No attempt was made to separate them with heavy liquids, and the percentage was determined from the average of a number of counts. In several soils the iron inclusions and stains in the pores of the grains were so dense that it was impossible to determine the mineral until they had been washed with an acid. From several of the soils a magnetized pocketknife separated magnetic grains of a red color. These grains were analyzed and found to be almost entirely ferric oxide (Fe_2O_3). No inner core of magnetite was discovered in these grains. Below are recorded results of the mineralogical examination:

No. 8833. Red. Orangeburg clay, subsoil, 2.5 miles south of Jacksonville, Tex. Minerals other than quartz, 5 per cent. Quartz nearly all secondary. The secondary quartz grains inclose iron oxide. Four per cent of magnetic hematites are present. Limonite and weathered orthoclase present in some quantity. Tourmaline, zircon, and biotite are common accessories.

No. 16478. Red. Decatur clay loam, subsoil, 2.25 miles south of Rendalia, Talladega County, Ala. Minerals other than quartz, 3 per cent. The ratio of secondary to primary quartz is 5 to 1. Magnetite and magnetic hematite present in some quantity. Feldspars present and in an advanced state of alteration. Microcline, muscovite, and hornblende present as accessories. The secondary quartz crystals are double terminated and carry inclusions of iron oxide.

No. 8118. Red. Orangeburg sandy loam, subsoil, 1.5 miles southwest of Mosebys Cross Roads, Gadsden County, Fla. Minerals other than quartz, 2 per cent, of which the following minerals predominate in their order of importance: Sillimanite, tourmaline, hornblende, zircon, rutile, and ilmenite. The ratio of secondary to primary quartz is 1 to 3.

No. 14793. Red. Miller clay, subsoil, southwest corner sec. 7, T. 14 N., R. 1 E., Oklahoma County, Okla. Minerals other than quartz, 4 to 5 per cent. The ratio of secondary to primary quartz is 3 to 2. Orthoclase present and very much altered. Microcline present in some quantity. Hornblende (green), tourmaline, and zircon present in small amounts. Many of the secondary quartz grains inclose iron oxide.

No. 7180. Red. Cecil clay, subsoil, Crossroads, southeast of Moormans River, Albemarle County, Va. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 5 to 1. Biotite present in large quantities. Magnetic hematites are present and show a red surface. Hornblende, tourmaline, epidote, and zircon occur as common accessories. The secondary quartz grains are stained with iron.

No. 9230. Red. Penn clay, 4 miles west of Baldwinsville, N. Y. Minerals other than quartz, 15 per cent. The ratio of secondary to primary quartz is 2 to 1. Feldspars, microcline, and garnet abundant. The orthoclase is generally highly altered. Albite, magnetite, and microcline-microperthite are present. Green hornblende, showing alteration into chlorite, is present in some quantity. Biotite, epidote, zircon, and chlorite are present as accessory minerals. The secondary quartz grains inclose large quantities of iron oxide.

No. 5901. Red. Penn loam, subsoil, 1 mile southeast of Gainsburg, Dauphin County, Pa. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 1 to 1. The feldspars, consisting of orthoclase, albite, and microcline are fairly abundant. The orthoclase is very much altered and stained. Tourmaline, muscovite, and albite are common accessories. Fibrous epidote and hematite, both magnetic and nonmagnetic, are present in some quantities. The magnetic hematite shows a red surface.

No. 11318. Red. Orangeburg sand, subsoil, 1 mile southeast of Intercourse, Sumter County, Ala. Minerals other than quartz, 5 per cent. The ratio of secondary to primary quartz is 1 to 3. Hornblende, tourmaline, rutile, epidote, and zircon are present. The zircons are well rounded. Highly altered feldspars and cyanite are present in traces.

No. 11417. Red. Orangeburg sand, subsoil, N. ¼ headright 37, Twp. 5, R. 32 W., Escambia County, Fla. Minerals other than quartz, 3 per cent. The ratio of secondary to primary quartz is 2 to 3. Rutile and zircon are present in some quantity. A small amount of weathered orthoclase occurs. Tourmaline is present in traces.

No. 5328. Red. Cecil sandy loam, subsoil, 0.75 mile west of Amity Hill, Iredell County, N. C. Minerals other than quartz, 50 per cent. The ratio of secondary to primary quartz is 2 to 5. Feldspars, biotite, and chlorite make up the largest part of the minerals other than quartz. The biotites are in an advanced state of chloritization and are yellow in color, resulting from inclusions of iron oxide. Of the feldspars, microcline is the most abundant and usually does not show evidences of alteration; orthoclase, albite, and oligoclase occur in descending order of quantity. Zircon, tourmaline, rutile, and garnet occur as accessories.

No. 10675. Yellow. Norfolk fine sand, subsoil, Andells Bluff, S. C. Minerals other than quartz, 30 to 40 per cent. The ratio of secondary to primary quartz is 2 to 3. Hornblende present, 10 per cent; epidote, 5 per cent. The potash feldspars are abundant, the orthoclase showing characteristic alteration and the microcline practically unaltered. Zircon, inclosing rutile, is present in some quantity. Chlorite, biotite, tourmaline and rutile are present as accessories.

No. 5875. Yellow. Hagerstown loam, subsoil, 2 miles south of Lebanon, Lebanon County, Pa. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 3 to 2. Orthoclase is found in some quantity. It is very much altered, having stains of iron oxide deposited in the cracks. Microcline, acid plagioclase (albite and oligoclase) are present. Zircon, magnetite, and tourmaline are present as accessories. This soil is characterized by perfect quartz crystals.

No. 13714. Yellow. Lansdale silt loam, subsoil, 2 miles southwest of Phoenixville Chester County, Pa. Minerals other than quartz, 3 to 5 per cent. The ratio of secondary to primary quartz is 3 to 2. Partly weathered orthoclase makes up the greater part of the minerals not quartz. Biotite, hornblende, tourmaline and rutile occur as accessories. Microcline is present.

No. 7841. Yellow. Norfolk sandy soil, subsoil, 2.5 miles east of Darlington, Darlington County, S. C. Minerals other than quartz, 3 per cent. The quartz is mostly primary. Magnetite, zircon, rutile, and tourmaline are present. Biotite is present in a highly chloritized condition.

No. 5744. Yellow. Durham sandy loam, subsoil. Method, Wake County, N. C. Minerals other than quartz less than 2 per cent. The quartz is mostly primary, some carrying inclusions of magnetite and apatite. Tourmaline and yellow hornblende are most abundant of the minerals other than quartz. Rutile, zircon, and muscovite are present. Magnetite and ilmenite are present in traces.

No. 12827. Yellow. Dekalb clay, subsoil, 3 miles north of Buckhannon, Upshur County, W. Va. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 3 to 1. Biotite and muscovite are present in some quantity and are largely altered. Epidote, rutile, and zircon are common accessories. Chlorite is present as an alteration product. Tourmaline is present. The minerals show an advanced stage of alteration and very few of the femic minerals occur in the unaltered condition.

No. 6417. Yellow. Memphis silt loam, subsoil, 10 miles south of Yazoo City, Yazoo County, Miss. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 2 to 5. Quartz grains carry inclusions of microcline. Microcline, biotite, and tourmaline are the most abundant of the minerals other than quartz. Biotite shows alteration into chlorite. Zircon and hornblende are common accessories.

No. 13338. Yellow. Dekalb loam, subsoil, 0.5 mile south of Hinkleville, Upshur County, W. Va. Minerals other than quartz, 10 per cent. The ratio of secondary to primary quartz is 2 to 1. Feldspars are present and in an advanced state of decomposition. Biotite, tourmaline, and zircon are present. Epidote occurs as an alteration product of feldspars.

No. 6258. Yellow. Norfolk fine sandy loam, subsoil, 3 miles north of Vanceboro, Craven County, N. C. Minerals other than quartz, 5 per cent. The ratio of secondary to primary quartz is 1 to 5. Quartz grains carry inclusions of liquid, gas, and fine needles of rutile. Microcline, zircon, tourmaline, hornblende, magnetite, ilmenite, and titanite occur in descending order of quantity.

No. 13578. Yellow. Dekalb fine sandy loam, soil, 3 miles east of Berea, Madison County, Ky. Minerals other than quartz, 5 to 7 per cent. The ratio of secondary to primary quartz is 5 to 3. Feldspars are present in a highly altered condition. Tourmaline, hornblende, zircon, and biotite are present. Epidote and microcline are present in traces.

It can be seen from the mineralogical examination that there is a larger proportion of secondary quartz grains in the red soils than in the yellow soils. On the average, over 60 per cent of the quartz grains of the red soils are secondary, whereas less than 40 per cent of the quartz grains of the yellow soils are secondary. The average ratio of the secondary grains to the primary grains is nearly three times as much in the red soils as it is in the yellow soils.

It is probable that the red soils have resulted from the decay of rocks carrying large amounts of ferromagnesian minerals, the ferromagnesian silicates breaking up into their constituents, and the silica crystallizing as secondary quartz, and some iron oxide inclosed. Red soils may also be formed by long continued weathering of soils originally lower in ferric oxide.

Yellow soils have probably been derived from the acidic rocks, which are low in iron oxide and which carry a large proportion of quartz. This quartz has been crystallized from the molten magma as primary quartz grains. If, however, this soil be exposed to geological agencies for a long period of time, the more soluble portions of the soil will be weathered away, leaving the residue higher in iron oxide. As this process thickens the film formation described on a preceding page, there is a change in color from the yellow to the red, and as time goes on there will be eventually a red soil.

It has been noted previously by Cameron[a] that the soil is not by any means stationary, but is everywhere being moved about and mixed by various geological agencies. So it is that many times minerals from one type of soil are admixed with the minerals in soils of other types. This complicates the problem, for in many cases the minerals which are present in the rocks that form a yellow soil have probably been mixed with red soils, and vice versa, especially is this true of the minerals occurring in small amounts. The almost universal presence of zircon in the soils here examined is a good example of this intermixing. Zircon occurs in acidic rocks but is not found in basic rocks, and all these soils have not been derived from acidic rocks.

Epidote and hornblende, both easily decomposed iron-bearing minerals, are present in small quantities in the red and yellow soils alike.

From a consideration of the mineralogical data, it appears that basic rocks or rocks rich in the ferrous minerals will, on decay, yield a red soil. Red soils may also result from yellow soils by continued action of weathering agencies, where erosion is relatively small. This is due mainly to the extremely low solubility of ferric oxide, and its consequent tendency to segregate in the residue as the other constituents leach away.

Acid rocks, which are relatively low in iron-bearing minerals, will generally in decay give a yellow soil. Yellow soils have also been formed from red soils, where erosion agencies and water transport have been active. Ferric oxide, as a surface coating, is concentrated in the finer particles of the soils and erosive agencies are more effective in removing these particles, thus leaving a residue of the lighter colors.

The color of a soil is, therefore, an index to its age, but must be considered in connection with other data more or less readily determined by accepted geological methods. From the fact that the minerals in the red soils commonly show greater weathering than do the minerals of yellow soils, it is apparent that red soils are usually older than yellow soils derived from the same material. The reverse case, where the yellow soil is older than the red soil derived from the same material, is much less common.

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[a] Jour. Ind. and Eng. Chem., 1, 807 (1909); Jour. Phys. Chem., 14, 320 (1910).

SUMMARY.

From the foregoing pages it appears that:

(1) The color of a soil has important agricultural significance. Dark-colored and red soils are generally warmer and better drained than light-colored soils. Certain extreme cases are, however, exceptions to the general rule, as is the case of bogs and peats on the one hand and stiff red clays on the other hand, of which the Susquehanna clay is a striking example.

(2) Generally speaking, the color of a soil is dependent upon the content of organic matter and ferric oxide, the latter being more or less hydrated.

(3) The thicker the film of organic matter and ferric oxide coating the soil grains the darker the soil.

(4) Organic matter tends to blacken a soil. Intermediate shades of gray are fairly common. Ferric oxide tends to redden a soil. Intermediate yellowish shades are known, but not common. Organic matter and ferric oxide together produce shades of brown, which are very common.

(5) The degree of hydration of the ferric oxide in red soils may be less than in yellow soils. That such is the case, however, has never been shown, and it is probable that the thickness of film surrounding the soil particles is the predominant factor determining color.

(6) Ferric oxide is the soil component least soluble in pure water and most salt solutions. It is easily reduced to the ferrous condition by the soluble organic soil components and is then soluble to a marked degree in the presence of carbon dioxide. Its transportation in the soil is explained by these facts.

(7) Ferric oxide tends to segregate in surface soils and on or among the finest or "clay" particles.

(8) Generally, although not always, red soils are older than yellow soils, and the drainage is better.

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